The economics of malaria control

Opportunities, incentives, and risks on the road from control to elimination

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"Nature hath framed strange fellows in her time."

The Merchant of Venice
William Shakespeare

ACCOUNT OF STUDIES

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1. **Researchers' perceptions of malaria eradication: findings from a mixed-methods analysis of a large online survey**. Brew J, Pradhan M, Broerse J, Bassat Q. *Malaria Journal*. https://malariajournal.biomedcentral.com/articles/10.1186/s12936-020-03430-2

2. **Foreign direct investment, corporate social responsibility, and malaria control in Mozambique - trends, risks, and opportunities.** Brew J, Aerts C, Sicuri E. *African Development Review* (under review). https://github.com/joebrew/fdi_moz

3. **Evidence of high bednet usage from a list randomization in rural Gambia.** Brew J, Pinder M, Dalessandro U, Lindsay SW, Jones C, Sicuri E. *Malaria Journal*. https://dx.doi.org/10.21203/rs.2.17453/v1

4. **A systematic review of the incremental costs of implementing a new vaccine in the expanded program of immunization in Sub-Saharan Africa.** Brew J, Sauboin C. *Medical Decision Making Policy & Practice*. https://doi.org/10.1177%2F2381468319894546

5. **Mapping the potential use of endectocide-treated cattle to reduce malaria transmission.** Imbahale S, Montaña J, Brew J, Paaijmans K, Rist C, Chaccour C. *Nature Scientific Reports*. https://www.nature.com/articles/s41598-019-42356-x

6. **Is malaria control profitable? Return on investment of residential fumigation at a sugarcane processing facility.** Brew J, Sicuri E, Pradhan M, Gondo K. Intention to submit to *Journal of Health Economics*. https://docs.google.com/document/d/1bUWRBCgVcgjSPHchIQxiTG8Vwv5hV1GLU4Tlu386sWA/edit#

CONTENTS

1. Introduction

1.1 General Introduction and problem statement

The ever-present problem of malaria

Malaria is among the oldest diseases known to humankind. References to seasonal fever outbreaks appear on clay tablets from Mesopotamia (Institute of Medicine, Board on Global Health, and Committee on the Economics of Antimalarial Drugs 2004). Ancient Egyptian, Indian, Chinese, and Greek literature all contain references to malaria ("Malaria: A Brief History" 2016), and the name itself (meaning "bad air") (Hempelmann and Krafts 2013) evokes a bygone era when much was known about the firsthand experience of the disease, but little was known about its transmission. In his essay "On Airs, Waters, and Places", Hippocrates spoke of "marsh fevers" among those who lived near water (Hippocrates 2007). This general understanding that the quality of air was malaria's causal agent persisted until the 1800s.

Prior to humanity's understanding of the origins of malaria, progress in malaria control was likely accidental. That is, urbanization and industrial water management led to reductions in malaria's burden even though these reductions did not figure into the intentions of those carrying out the interventions. That said, the changing epidemiology of malaria, caused by the changes to landscapes which came from industrialization, may have figured into Charles E. Johnson's challenge of the millenia-old "miasma" (bad air) theory. "These are some of the facts and circumstances which have induced me to abandon the miamatic hypothesis", he wrote to his colleagues in 1851. "No chemical analysis, so far, has been able to detect [miasma]; no microscopic investigation… there is no truth in the doctrine miasmatic origin of disease" (Johnson and Medical Society of the State of North Carolina 1851).

Scientists' understanding of malaria was accelerated by the economic incentives that came with colonialism. To some extent, the emergence of the field of "global health" itself came as a result of the magnitude of the problem of fever among colonists. After all, as Albert Freeman Africanus King wrote in 1883, "of all human races the white is most susceptible to marsh-fevers, the black least so" (Daniels 1950). Imperial Europeans and Americans needed to better understand the origin of tropical fevers in order to mitigate their economic effects, and with these incentives aligned, progress came quick. By the late 20th century, colonialism-fueled science had made clear that malaria was mosquito-driven. By the end of the century, the aetiological mystery was solved: parasites were observed in a malaria-stricken patient's blood (Anderson and Laveran 1893).

With this knowledge in hand, and with most of Africa colonized by Europeans, the early 20th century saw rapid progress in malaria control. Much of it continued to be the secondary effects of economic development (specifically from swamp drainage and housing improvement), but pesticides targeting the malaria vector – the mosquito – also played a significant role. As of 1900, it is estimated that 53% of the world's surface was at risk of malaria; a century later, that number was sliced in half to 27%. In terms of population, this meant a reduction from 77% to approximately 50% (Hay et al. 2004). In other words, the

path to global eradication had begun, even though eradication was not a familiar concept to the scientific community at the time.

Success in suppressing seasonal malaria outbreaks coincided geographically and temporally with colonial development projects. In the Panama Canal zone, greater than 1% of workers died annually due to malaria in 1906; 3 years later, thanks largely to environmental health interventions, that number was reduced to approximately 1 in 1,000 ("The Path between the Seas: The Creation of the Panama Canal, 1870-1914," n.d.). Though the malaria control interventions – swamp drainage, bush cutting, larviciding, quinine distribution, and door and window screening – were primarily aimed at protecting workers, there was a positive spillover to nearby local populations: deaths from malaria for the population at large dropped from 16 per 1,000 in 1906 to 2.6 per 1,000 in 1909 (CDC-Centers for Disease Control and Prevention 2009). Though the overall effect of the canal on health is difficult to quantify, in the specific realm of malaria, it is clear that public health benefited from private malaria control.

Similar privately-driven malaria control interventions were taking place simultaneously in other parts of the world. In Asia, malaria control was driven largely by plantation owners (Watson 1908), whereas in Africa it was largely mining operations (Utzinger et al. 2002). Latin America also saw a mix of malaria control efforts at large mines and plantations (Killeen et al. 2002). These campaigns were decentralized, had no ambitions of elimination, and only had limited public health intentions, and were primarily profit-driven. Progress in malaria control continued through the first half of the 20th century, but not at the explosive rate of the century's first decade (Ward and Harrison 1979).

Whereas the early century jump in malaria control progress was largely due to infrastructural improvements, and driven by colonial ambitions, malaria control went through another acceleration phase in the mid-20th century, thanks to both chemical and geopolitical factors. The chemical factor was the wide scale emergence of DDT (dichlorodiphenyltrichloroethane) as an insecticide, and the geopolitical factor was (a) the deployment of European and American troops to the Pacific during the second world war followed by (b) the emergence of supranational organizations (United Nations and the World Health Organisations) thereafter.

The eradication era

"Now we know exactly… the schedule of an eradication campaign which will last four or five years followed by three years of consolidation"

-UNICEF Americas Regional Director, September Meeting, New York, 1955

The "eradication era" refers to the 2-decade period following the second world war (Hay et al. 2004). During this time, large "first-world" countries eliminated malaria (or came effectively close to elimination) thanks to (a) the resources available in the post-war economic boom, (b) the use of DDT, and (c) large-scale infrastructure projects in water management. The United States, along with southern Europe and parts of Northern Africa, also reduced annual autochthonous malaria cases to zero. In light of this progress, the World Health Organisation (WHO) set out on what at the time seemed a realistic campaign to completely eradicate malaria: in 1955, at its 8th World Health Assembly, the Global Malaria Eradication Programme (GMEP) was announced. The change in strategy was

radical, but meant to be radically transformative. Instead of the decentralized approach which characterized the early 20th century's progress, the GMEP would oversee a global, expert-driven campaign to eliminate malaria even from those areas where the stand-alone costs of doing so might otherwise not be deemed reasonable.

The eradication era ended almost as abruptly as it began. Though the centralized approach and ambitious vision helped foster support and donations, when expectations diverged from reality (as was the case in the massive resurgence of malaria cases in near-elimination contexts like Sri Lanka), disillusionment set in ("Malaria Consortium" n.d.). Furthermore, the top-down approach was successful in mobilizing resources, but was not able to integrate into local healthcare systems or respond differentially to the distinct social, political, and economic realities of malarious regions. In some ways, the cause of the GMEP's ambitious optimism – the effectiveness of DDT – was also in part the reason for its decline. By the time Rachel Carson published "Silent Spring" in 1962 (Drury 1963), documenting the adverse environmental effects caused by the widespread use of DDT, it had already become clear that the GMEP would not succeed in its mission. The "eradication era" ended, and malaria resurgence followed. By 1969, in light of stalling progress, parasite resistance to chloroquine, mosquito resistance to DDT, and shrinking donations, the WHO formally abandoned the campaign (Mendis et al. 2009).

Success with country-specific elimination: another chance at eradication?

From the 1970s through the 1990s, progress towards malaria eradication was stalled. Efforts were primarily at the national-level and aimed firmly at control rather than elimination. Political instability in recently independent African states lead to an outsized role of the private sector for malaria control. As with the early century's mining and plantation initiatives, these activities had positive public health externalities, but public health was not their primary intention. Malaria increased in some areas and decreased in others, but on the whole progress had stalled, or even reversed. Given the decreasing effectiveness of the arsenal of tools due to increasing resistance, deaths from malaria increased through the 1990s (Trape et al. 1998).

In reaction to these changes, and thanks to new therapies and interventions, at the turn of this century, the world community began looking again at national elimination, and worldwide eradication, as realistic goals. The Bill and Melinda Gates Foundation began active involvement in financing ambitious malaria projects in the early 2000s (Gross 2003). In response, a Lancet Editorial in 2007 asked the question "Is malaria eradication possible?"; the response was ambiguous, but characterized Gates' initiatives as "rightly challenging the global health community to ask itself whether it should not be more ambitious" ("Is Malaria Eradication Possible?" 2007).

That ambition emerged over the next decade. Researchers and funders began shifting their sights from control to elimination and eradication. The tone changed from eradication being a "challenge" to being a "goal" (Lancet and The Lancet 2011). The frequency with which the words "elimination" and "eradication" appeared in the research literature began to increase to levels not seen since the mid-century GMEP era (see figure 1.1). The conversation shifted from "if" to "how" and "when".

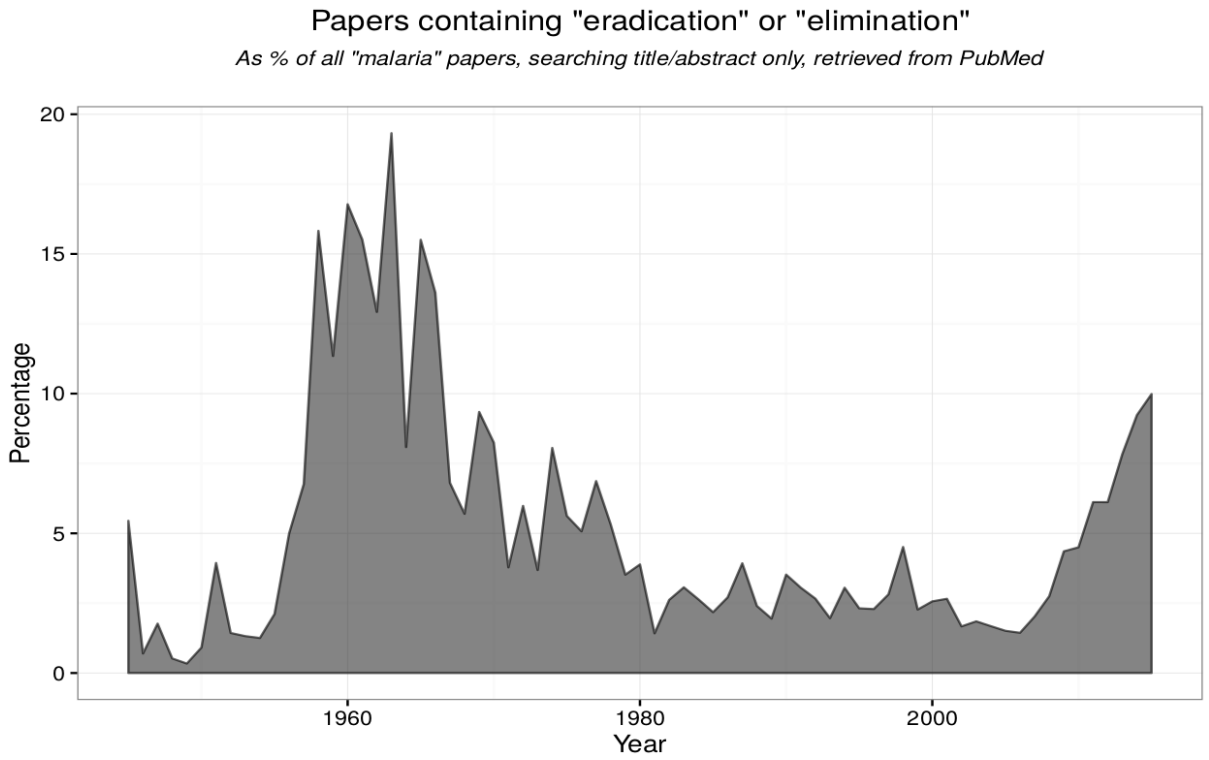

Figure 1.1: Percentage of papers on PubMed containing the terms "eradication" or "elimination" in the title or abstract, among all papers containing the word "malaria". Data from PubMed; data aggregation and chart by Joe Brew.

Researchers were determined not to repeat the mistakes of the previous "era of eradication". An evidence-based research agenda was established (Alonso et al. 2011), and energy began to consolidate. In 2014, Bill Gates declared that malaria could be eradicated "within a generation". In 2015, the WHO set the goal of eliminating malaria in 35 new endemic countries in 15 years, and reducing all deaths by 90%. Everything, it seemed, was in place for rapid progress towards eradication.

Progress towards elimination and eradication efforts slowed, however, towards the end of the decade (see Figure 1.2). From 2015 to 2017, 55 countries saw an *increase* in the number of malaria cases. The WHO Strategic Advisory Group on Malaria Eradication (SAGME) acknowledged "stalling progress" and that meeting the 2015 targets was "unlikely" (World Health Organization 2019). And though the Lancet Commission argued that global eradication by 2050 was both a "necessary" and "attainable goal", the timeline mentioned was 2050 (Feachem et al. 2019).

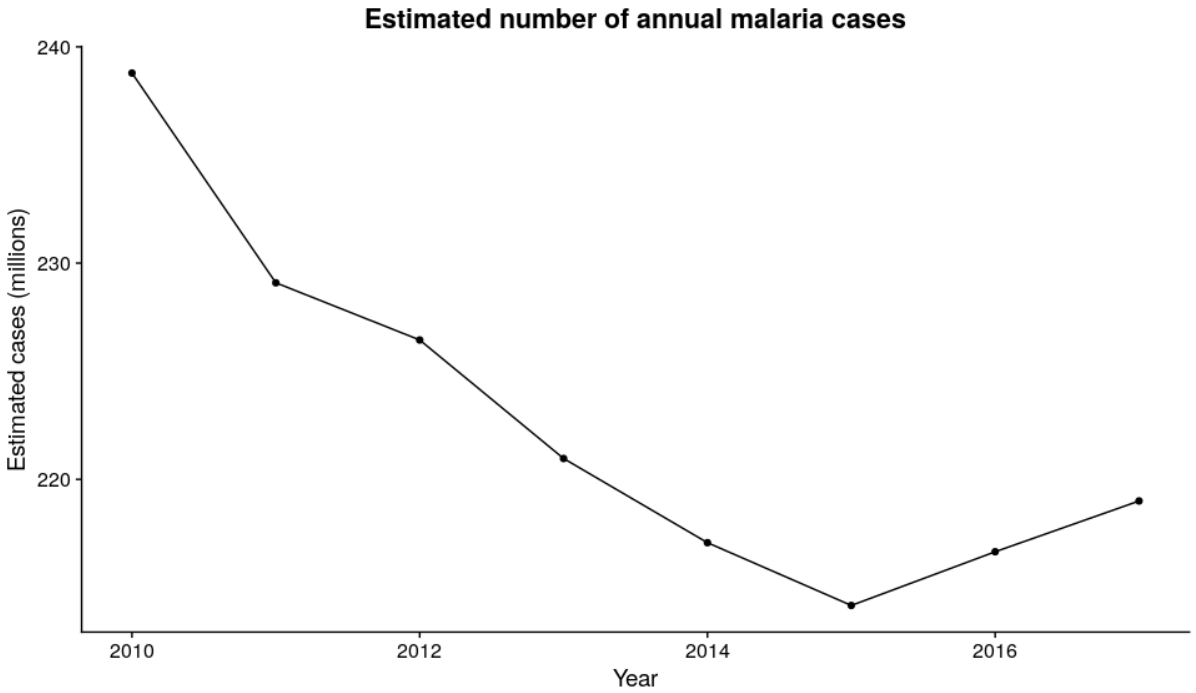

Figure 1.2: Estimated total number of annual malaria cases. Country-level data from the World Health Organization (https://www.who.int/data/gho/data/indicators/indicator-details/GHO/estimated-number-of-malaria-cases); data aggregation and chart by Joe Brew.

Problem statement

As was the case with the 1950s-60s eradication campaign of the WHO GMEP, stalling progress has forced the leaders of the world's second eradication campaign to soften their goals and timelines. In its most recent report, the WHO SAGME states that "we are certain that eradication by a specific date is not a promise we can make to the world just yet" (World Health Organization 2019). In other words, though the case for eradication is compelling, the research agenda is clear, and the technical requirements all seem to be in place, reality has – once again – diverged from expectations. History has, to some extent, repeated itself.

All the puzzle pieces for global malaria eradication appear to exist. Prevention methods are well-known, culturally acceptable, largely safe, and fairly affordable. Testing is rapid and cheap. Treatment is effective and almost universally available. Why then, again, does progress stall?

Malaria is what management scientist C. West Churchman might describe as a "wicked problem" (Surhone, Timpledon, and Marseken 2010). Like other "wicked problems", the characteristics of the problem and the resources available for solving it are in constant evolution, stakeholders in the issue have diverging views, and it is unique in both scope and nature. By the same token, the "solution" to the malaria "problem" depends on how the problem is framed – whether one says the problem as one of biomedical, geopolitical, or economic in nature.

Wicked problems are notoriously difficult to solve. Management research in the area suggests that progress is generally made when the problem is appropriately structured, and such a structuring requires the incorporation of new actors and viewpoints. In “Addressing Wicked Problems through Transdisciplinary Research” (Surhone, Timpledon, and Marseken 2010; Pohl, Truffer, and Hirsch-Hadorn 2017), Pohl and his collaborators argue that the “recursive” and “inclusive” nature of transdisciplinary research can help in problem identification and structuring, since only an incorporation of all stakeholders’ views can lead to a comprehensive understanding of the true scope of a problem.

The problem of malaria is fundamentally one of (a) functional pieces and (b) a broken whole. The components for eliminating the disease entirely appear to exist, but the alignment of those components does not. In human behavior, collective alignment is a function of individual incentives. So, the reasonable conclusion one might make in trying to frame the problem of malaria is that the incentive must not exist, at the individual level, for eradication to take place (I specify the *individual* level, because it is clear from the evidence that the incentives at the *collective* level are more than abundant).

In this sense, national malaria elimination and global malaria eradication, and even local malaria control (to a lesser extent), can be conceptualized as a “public good” in that it is non-excludable (ie, it is not possible to exclude one from the positive externalities of another’s activities). Non-public actors (individuals and private firms) contribute to the production of this public good, but can be incentivized to contribute insufficiently to it, particularly when larger actors contribute disproportionately (Olson 2009). In this framing, an actor’s decision to “participate” or not in the provisioning of the public good of malaria control is a function of both that actor’s wealth, but also the relative distribution of wealth among other actors poised to potentially provision the same good (Bergstrom, Blume, and Varian 1986). Concretely, there may be a tendency for smaller actors (individuals and firms) to attempt to create the conditions in which larger actors (governments and international agencies) bear the burden of the provisioning of the good solely.

The fundamental irony of wicked problems is that defining them is itself part of the wickedness. That is, if the problem were easily defined, it would not be wicked. Thus, stating that individual incentives are not sufficient for the global eradication of malaria, or national elimination in many cases, is overly simplistic. The *wickedness* of the problem is in identifying where those incentives are missing, how they can be modified, and what mechanisms can be used to monitor the effect of their modification (and the unintended side-effects).

Tackling a wicked problem can be carried out using one of three strategies: (1) Collaborative, (2) Authoritative or (3) Competitive (Roberts 2000). Whereas the 1950s-60s GMEP campaign might be described as authoritative (insofar as it was centralized and sought to reduce the complexity of malaria by applying a one-size-fits-all approach), one might characterize the current eradication effort as collaborative, in that it strives to incorporate researchers and public health stakeholders in a more decentralized manner. But both the authoritative and collaborative approaches have, as discussed, lead to suboptimal progress towards the stated goals of eradication. Why is that?

My ingoing definition of the malaria problem is not that the tools available are inadequate, but rather that the incentives for their adoption are insufficient. This insufficiency of incentives assumption in some ways puts my research more in line with what Roberts' would call the "competitive" approach to wicked problem resolution. But I would argue that the malaria problem is more complex than her rubric permits. Harnessing competitive forces can be useful to progress in malaria (as was evidenced by the self-interested gains in malaria control from colonial efforts), but is not sufficient. The nature of malaria as a disease is in itself at the crossroads of competitive and collaborative dynamics, and is not without a dose of authoritative elements (i.e., medical professionals exercise a high, and necessary, degree of authority in terms of prevention and treatment regimens).

The insufficiency of incentives assumption leads me to a research approach grounded mostly, but not exclusively, in the science of economics, dealing fundamentally with the question of the problem of incentives. That is, if eradication is possible, why hasn't it been achieved? And if elimination in most Sub-Saharan countries were possible, why hasn't it been achieved? Why do we *choose* not to eradicate malaria, and what factors influence those choices?

To bring the problem definition back to a more concrete space, let us return from the problem of malaria to what this dissertation does and does not do. Having defined the problem of malaria as one of sufficient means but insufficient incentives, my research focuses on the economic questions surrounding malaria control, elimination, and eradication at both the individual, firm, and societal levels with a particular interest in quantifying the costs of health interventions and their effects. It also takes a multi-stakeholder perspective and will explore the disconnect between what people say and what they do, among both those who research and those who are researched, since this disconnect fundamentally informs and misinforms our understanding of the malaria problem.

This dissertation does *not* "solve" the problem that it defines (the insufficiency of incentives for aggressive malaria control, national elimination, or global eradication), nor does it even aim to. On the contrary, in line with the "recursive" principles of both transdisciplinary research and "wicked problem" strategy research, this dissertation adopts the more modest mission of "shifting the goal of action on significant problems from 'solution' to 'intervention'" (Knapp n.d.). In summary, if we accept the assumption that the component technical pieces of effective malaria control already exist, and therefore recognize that among the principle impediments to eradication are the insufficiency of incentives, our problem definition is not the resolution of those insufficiencies, but rather the identification of those incentives. And identifying incentives requires a quantification of factors involved, which brings us to the specific research aims of this dissertation.

1.2 Research aims

The general aim of this research is to gain insight into incentives for and against malaria control and elimination by (a) exploring unexploited partnerships with atypical stakeholders in malaria control through a quantification of costs and benefits of engaging in malaria control activities; (b) assessing uncertainty in regards to the cost of control and elimination-related interventions; (c) calculating the likelihood and time-scale to eradication,

as well as facilitating factors and barriers; and (d) assessing the reliability of some of the data we use to gauge control-related activities.

2. Theoretical background and framework

Any analysis which seeks to generate knowledge regarding health or economic behaviors requires a clear theoretical understanding of the reasons the decisions resulting in those behaviors are made. Investment in health – either at the individual level through health-seeking prevention methods such as sleeping under a bednet, or at the collective level through investment in measures which improve the health of a firm's workforce – is not taken lightly by anyone who carries it out. On the contrary, the temporal nature of investment in its most broad sense (an up-front cost for a later payout) requires the incorporation of concepts like cost of capital, discounting, opportunity cost, and risk.

2.1 Human capital theory

Perhaps the most obvious starting point for a theory of what determines investment and behaviors in malaria-related activities is the canonical paper by Michael (Grossman 1972) in which he argues that health is itself a depreciating asset which can be increased by investment This self-investment model, largely the foundation for the human capital theory insofar as it is applied to health economics, could be largely extrapolated to firms' behaviors. However, Grossman's focus is primarily at the micro-level, and because of this focus on the individual, he reduces complex systems of poverty (inherent to any analysis of malaria) to person-level variables such as individual education. In other words, while Grossman's theory of health capital is not necessarily incompatible with a systemic analysis of the factors which influence malaria-related decisions, it is at least incomplete.

More contemporary theories offer more nuanced approaches. Abel expands Grossman's somewhat reductionist approach to investing in health to incorporate cultural elements and normative beliefs, which transcend spectrums like education (Abel 2008). Many others have also expanded definitions outwards, terming concepts like "symbolic capital" to account for the extent to which the narrow-visioned understanding of capital as "money" from the Grossman area failed to explain why people engage in many health-related behaviors that have no financial or explicit biological "return on investment" (Schneider-Kamp 2020). Though more nuanced, contemporary theories are not so much a departure from Grossman than a re-casting of capital theory into a slightly more refined version of itself.

Though incomplete, human capital theory remains the most compelling theoretical framework for understanding the interplay between health and wealth insofar as decisions are made. For this dissertation, I assume those basic arguments of Grossman that (a) one can self-invest in health as a form of capital; (b) the return on that investment in its most basic form is production in the unit of health time; and (c) that health can also be an end unto itself (i.e., not "converted" back in to capital-producing production hours). That said, I go beyond Grossman's initial theory in that (d) I put emphasis on the collective nature of health-related decision-making (as opposed to a individual model), and (e) I strive to incorporate economic resources not only as "environmental variables" which the individual can adjust to his or her liking, but as true constraints which bound decision sets in unique

ways over both space and time. In other words, scarcity sets real boundaries on investment decisions, both for individuals and organizations.

In addition to this variation on human capital theory, this research broadly incorporates the perspective of two further theoretical frameworks: (1) rational choice theory, and (2) the social-ecological model (SEM). The former provides the grounding on which we understand the inherent rationale behind individuals' and firms' decisions in regards to malaria-reducing activities, whereas the latter allows for an understanding of the factors which influence those decisions (i.e., why an investor chooses to spend money on malaria control activities, or why a villager chooses to sleep under a bednet).

2.2 Rational choice theory

Rational choice theory is the straightforward perspective of individuals maximizing their utility based on a consistent criterion and a limited options set (Eriksson 2011). Utility maximization is useful at the micro-level (in understanding why, for example, a person chooses to sleep under a net or answer a question in a certain way), but also at a macro-level (for understanding why and under what conditions firms invest in the health of their workers, countries in the health of their citizens, and supranational funders in the health agencies of countries).

Rational choice theory underlies most economic studies, and plays an important role in each of this dissertation's studies. However, beyond the specifics of each research question and the underlying assumptions in the methods used to address those questions, rational choice theory also plays an important role in the overall structure of this dissertation. As mentioned, my ingoing assumption towards the problem of malaria control is not an inadequacy of methods (the technical solutions for controlling malaria exist already, and the funding is arguably available), but rather an insufficiency of incentives.

Examining this insufficiency cannot be carried out at only one-level. At the macro-level, there is more than ample evidence that the benefits of malaria eradication would outweigh its costs (Sachs and Malaney 2002). At the micro-level, however, the utility of anti-malaria interventions is constrained by the options set (i.e., someone who is hungry may get more utility from a bednet as a fishing net); whereas once we mix levels, the incentives begin to become more complex and difficult to define. For example, a private firm may recognize that controlling malaria maximizes its own utility, but it may also be cognizant that by not engaging in malaria control activities, the government might step in and finance them. The interactions between these systems is why the theoretical framework of this study understands rational choice to be embedded *within* the social-ecological model, rather than a competing or separate framework.

2.3 Social-ecological model

Rationale choices do not exist in a vacuum; they are bounded by situational elements over which the chooser has varying degrees of control. The social-ecological model posits that individuals and environments exist in a complex, interactive system, and cannot be examined in isolation without a consideration of both their underlying and overlying

components (Golden and Earp 2012). It is a natural fit for transdisciplinary research insofar as it seeks to break out of narrow discipline scopes by understanding multiple levels of influence and interplay: the individual, the interpersonal, the organization, and the community (Bronfenbrenner 2000). It also fits well with the nature of this research in that it incorporates bi-directional causality; that is, it understands micro-systems as subject to the conditions of their multiple levels. To make this relevance more concrete, consider the nature of the act of sleeping under a bednet: it is conditioned by the family's ability to purchase or receive a net (micro), the society's aversion to or acceptance of nets (meso), the country's health budget or the amount of malaria-specific aid it received (exo), and the general research and funding climate on malaria elimination and eradication (macro). By the same token, each of the aforementioned systems exercises reverse influence as well. The general research and funding climate for malaria (macro) changes in light of national-level "successes" or "failures" (exo), which in turn are determined by how society perceives and relates to malaria control interventions (meso), which are themselves subject to whether an individual sleeps under a bednet or not (micro). A highly stylized example of these factors is in figure 1.3.

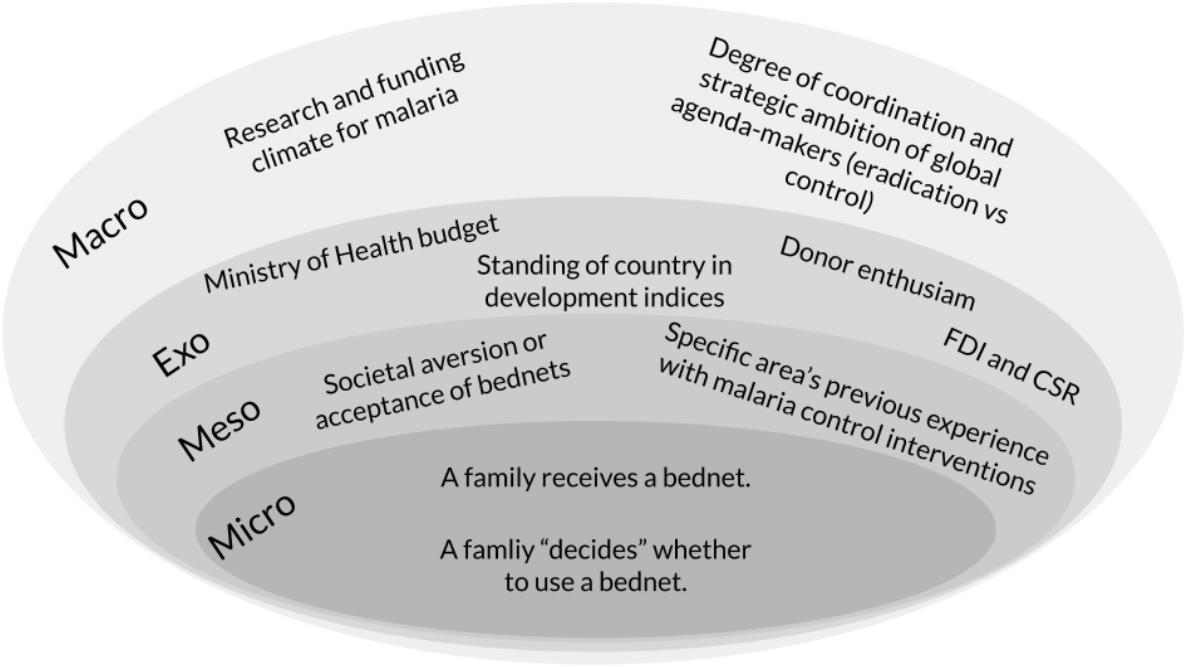

Figure 1.3: Example of the interplay of multi-level factors in a family's "decision" to use a bednet.

The social-ecological model is particularly relevant to my research into unexplored opportunities for collaboration with the private sector as well unexplored opportunities for health interventions. Taking a perspective which sees malaria not as a medical problem, but rather a problem at a myriad of levels (individuals, societies, countries, etc.) lends itself to stumbling upon the insight that malaria is also a problem *for* the private sector. In other words, with a social-ecological perspective on the private sector's role in malaria control is one that recognizes firms as "stakeholders" unto their own right, in the sense that they can be both beneficiaries of the public good of malaria control as well as contributors to it. Seeing the private sector as an equal stakeholder and potential partner in control also lends to identifying them not only as knowledge recipients (the typical stance of academia), but also knowledge generators; after all, many firms carry out malaria control activities during a

far longer period than the typical study protocol would permit (and thereby acquire significant amounts of knowledge).

The social-ecological perspective on the problem of malaria also helps to nudge one towards atypical solutions, and peripheral models. For example, if one accepts that the causes of malaria are not strictly biomedical (i.e., the usual academic definition of infection by parasite via vector), one naturally begins to look for solutions which are not located on that strictly biomedical causal pathway, but rather part of the epidemiological triangle(Gulis and Fujino 2015). This mindset, in essence, is what drives forward feasibility studies about interventions which have not yet taken place. These exercises in quantifying the benefits and costs of hypothetical future scenarios require an understanding of causal pathways which is not limited to viewing malaria as a strictly biomedical, individual-level, domain-specific problem. Quantifying the costs of a not yet invented vaccine and identifying ways to optimize the roll-out of a not yet proven antiparasitic drug requires “moving beyond parochial perspectives” (Aguirre et al. 2019).

2.4 Reconciling multiple frameworks

Utility maximization – the core tenant of rational choice theory – is assumed in all studies, and fits squarely within human capital theory. In fact, one could make the case that human capital theory is itself an attempt to reconcile traditional theories around capital-seeking behaviors with economics’ inability to understand health-seeking behaviors. Both rational choice and human capital theory would present decisions around eradication-related investments as potentially “solvable” insofar as one could estimate the correct parameters for each actors’ utility functions and health expectations.

It may appear, however, that these two frameworks are at odds with the social-ecological model. After all, the social-ecological model for behavior emphasizes complex associations in its explanation of behaviors, whereas rational choice theory reduces these complex associations to one utility function. This dissertation does not resolve this tension, nor does it strive to. Rather, it attempts to live within the tension, seeking to understand the landscape of malaria economics through that of rational actors living in a complex social-ecological environment. In other words, my conception of these theories, and my implementation of them into my research is one of containment: I understand individuals and firms to be rational, utility-maximizing actors (rational choice theory) existing in a complex, interactive environment with multiple, dynamic levels (social-ecological model).

3. Research Design

3.1 Research questions

The general research question driving this dissertation is: what are the incentives for and against malaria control activities?
The specific-questions are:

1. Where do opportunities exist for enlarging the body of stakeholders and funders involved in malaria control?
2. What is the likelihood of and time-frame to malaria eradication?
3. How much does malaria control cost?
4. What are the effects of malaria control and elimination activities?
5. To what extent can we rely on the data generated by malaria-related research?

The questions are addressed in six studies. The extent to which each study responds to these questions is viewable in table 1.

Table 1. Research questions addressed by each study (small x = tangentially addressed)

	Study number					
Research questions	1	2	3	4	5	6
Where do opportunities exist for enlarging the body of stakeholders involved in malaria control?		X			X	X
What is the likelihood of and time-frame to malaria eradication?	X					
How much does malaria control cost?				X		X
What are the effects of malaria control and elimination activities?			x			X

To what extent can we rely on the data generated by malaria-related research?	x		X	x		

3.2 Hypotheses

The ingoing, cross-cutting hypothesis to these research questions is that there exists an insufficiency of incentives for individuals and firms to invest meaningfully in malaria control and elimination measures. As with traditional laboratory research, I set out to disprove this null hypothesis by gathering evidence regarding malaria-related behaviors at both the individual and firm level, as well as perceptions regarding the utility of research data and feasibility of achieving eradication. This body evidence was formed with the following specific hypotheses in mind (each one pairable with its respective research question):

1. Significant opportunities for enlarging the body of stakeholders and funders involved in malaria control do not exist, because the economic incentives for scaled-up control efforts are not sufficient.
2. The likelihood of and time-frame to global malaria eradication, as perceived by malaria researchers, is lower and longer than institutional discourse would suggest; this gap can be explained by the need for institutions to project optimism in order to attract funding, and the hesitance of researchers to express pessimism for reasons of social desirability bias.
3. Malaria control is prohibitively expensive in many contexts, making scaled-up control (elimination efforts) economically unfeasible.
4. The economic effects of malaria control activities and interventions are positive, but not sufficiently sized to offset the financial costs.
5. The health effects of malaria control activities may be less than what researchers perceive via the biased data which they collect; this gap between reality and registration could partially explain the historical failure of eradication campaigns and the current stall in progress.

3.3 Research approach

This research was carried in the framework of “emergent design” (Schneider-Kamp 2020; Cavallo 2000). That is, the studies were not conceived in their entirety *a priori*, but rather emerged sequentially as results were generated and knowledge was acquired. As is typical in emergent design, the process of answering one research question satisfactorily required making assumptions, which in turn lead to more research questions. Though unstructured, the advantage of an emergent approach in this dissertation was that it allowed for the unanticipated information to find its way into the hypotheses generating and testing processes.

At a high-level, the research follows three cores themes:

First, I examine the role of the private sector in malaria control: that is, given that the public sector has not yet achieved the public good, which would be malaria eradication (even with some noteworthy collaborations with the private sector, such as the malaria vaccine), I explore the incentives for and impediments to the private, for profit, non-health sector scaling up their involvement in anti-malaria activities ("Foreign Direct investment, corporate social responsibility, and malaria control in Mozambique - trends, risks, and opportunities"), cognizant both that firms will be in large part the beneficiaries of control, but an overreliance on them creates a potentially unacceptable risk for society. In this same line, I go from macro (firms) to micro, carrying out an in-depth examination of one Mozambican sugarcane facility's absenteeism, clinical, and fumigations data so as to understand whether malaria control was "profitable" or simply socially "good" ("Is malaria control profitable? Return on investment of residential fumigation at a sugarcane processing facility").

Second, I seek to understand if the information systems researchers use for monitoring malaria interventions are themselves flawed: that is, perhaps we are mismeasuring the *inputs* of malaria control initiatives, and this mismeasurement could explain, at least to some extent, why the *outputs* of these initiatives have been disappointing. In this line of research, I examine whether bednet usage reporting might be tarnished by social desirability bias ("Evidence of high bednet usage from a list randomization in rural Gambia").

Third and finally, I seek novel data sources that allow for envisioning both how and when malaria eradication might be achieved. In this line of work, I elicit and aggregate views on eradication from 1,000 malaria experts ("Researchers' perceptions of malaria eradication: findings from a mixed-methods analysis of a large online survey"), identify opportunities where non-traditional cross-species interventions might be most effective ("Mapping the potential use of endectocide-treated cattle to reduce malaria transmission"), and quantify the roll-out costs of a hypothetical future malaria vaccine in Sub-Saharan Africa ("A systematic review of the incremental costs of implementing a new vaccine in the expanded program of immunization in Sub-Saharan Africa").

The below schema reflects a complex process distilled to its core components.

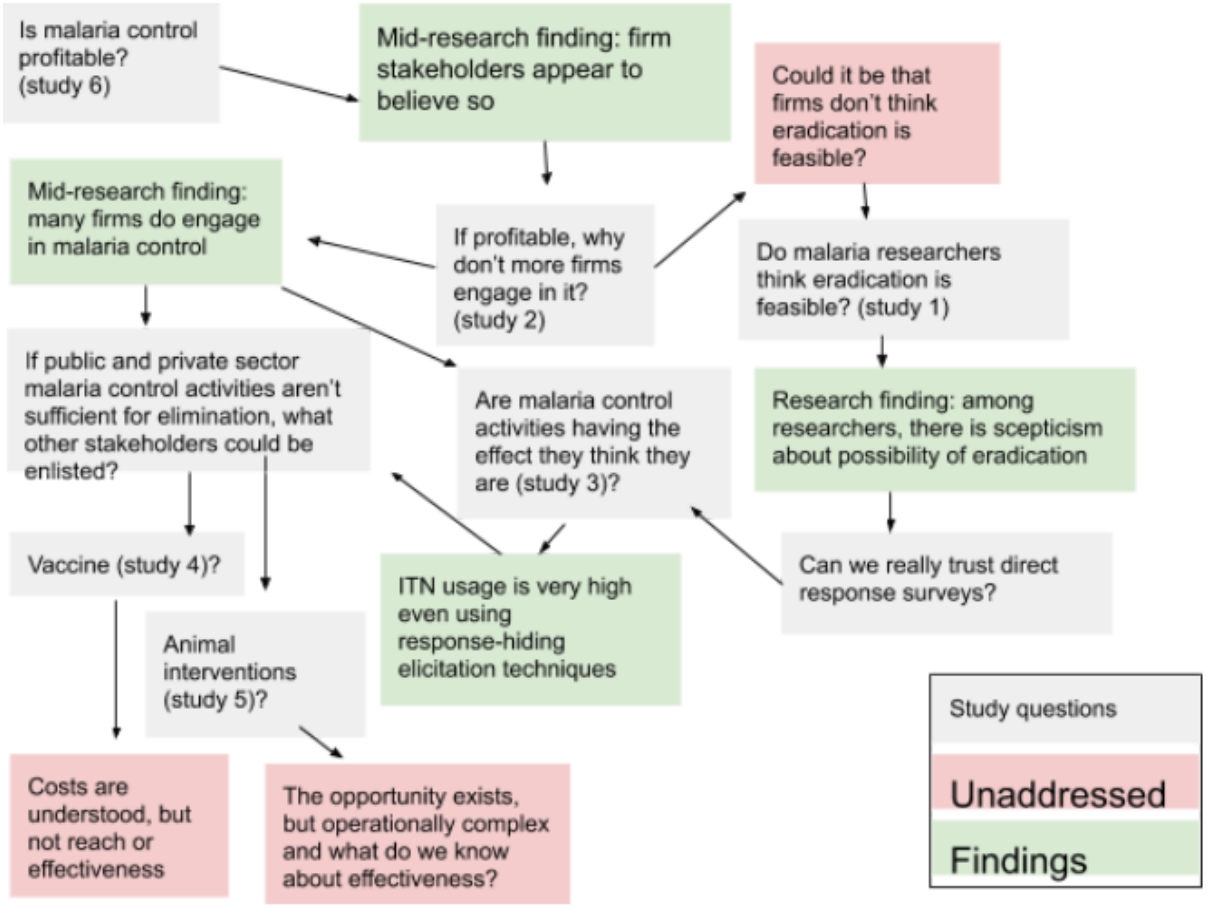

Figure 1.4: Rough overview of the "emergent design" approach of this PhD: questions leading to answers leading to questions, and so on.

3.4 Studies

The research of the thesis comprises six studies, which are each briefly presented below.

Study 1 – Researchers' perceptions of malaria eradication: findings from a mixed-methods analysis of a large online survey – sought to estimate the probability of, and time-frame to, global malaria eradication given researchers' perceptions on the matter. We carried out a large (n=844) online survey of peer-reviewed malaria researchers from a myriad of backgrounds, asking both quantitative and qualitative questions on when and whether eradication would occur, and what obstacles stood in the way. This was a mixed-methods study using both closed- and open-form questions. Analysis was both quantitative and qualitative. We found that researchers were more pessimistic than the position generally taken by institutional discourse, and explored implications for the expected value of the returns on eradication-specific investment.

Study 2 – Foreign direct investment, corporate social responsibility, and malaria control in Mozambique - trends, risks, and opportunities – aimed to explore the role of the private sector in malaria control in Mozambique. This was a mixed-methods study. Carrying out an analysis of publicly available datasets, and a systematic review of both grey

and academic literature pertaining to foreign direct investment and corporate social responsibility in Mozambique, we analyzed the issues and trends associated with the private sector's role in malaria control, and explored opportunities and risks for malaria elimination in the context of the private sector delivering a public good.

Study 3 – Evidence of high bednet usage from a list randomization in rural Gambia – employed a list randomization experiment to partially obscure respondents' answers to questions pertaining to bednet usage, so as to arrive at an estimate of true bendet usage with less social desirability bias. This was a survey of 196 participants carried out within the context of a larger randomized trial. We found that, even with the de-biasing method, estimates for bednet coverage were very high.

Study 4 – A systematic review of the incremental costs of implementing a new vaccine in the expanded program of immunization in Sub-Saharan Africa – combined data from a myriad of vaccine studies and programs in Sub-Saharan Africa in an effort to estimate the incremental cost of a hypothetical malaria vaccine. This was a traditional systematic review, albeit with a more developed quantitative component than most. Though we were able to generate an estimate for operational planning purposes, we found costs across programs to be hugely variable.

Study 5 – Mapping the potential use of endectocide-treated cattle to reduce malaria transmission – used publicly available data to identify a potential elimination opportunity than a non-traditional method; endectocide in livestock for malaria control. This was a spatial data analysis study. We found that the benefit of such a program would be highest in West Africa, where the prevalence of malaria among children, the density of partly zoophilic malaria vectors, and the density of cattle coincides to a large degree.

Study 6 – Is malaria control profitable? Return on investment of residential fumigation at a sugarcane processing facility – was an in-depth examination of the administrative data of a sugar mill in southern Mozambique. This was a retrospective return on investment study. Using absenteeism, clinical, weather, and fumigations data, we estimated both the costs and effects of the company's malaria control program, and quantified return on investment. Our results showed that, from a purely financial perspective, the program was profitable.

3.5 Ethics

Study 1 was given an exemption from the Scientific Committee of ISGlobal given that it did not deal with any health data. Study 2 used only publicly available data and involved no human subjects. Study 3 was carried out in the context of a larger housing improvement study. It was approved by the Gambia Government and Medical Research Council's joint ethics committee. Study 4 involved no human subject data. Study 5 used only publicly available data and involved no human subjects. Study 6 was approved by the Institutional Ethics Review Board for Health the Centro de Investigação em Saude de Manhiça (CIBS) prior to data collection.